

LAUNCH PAD LIGHTNING PROTECTION EFFECTIVENESS

James R. Stahmann
Boeing Aerospace Operations
Kennedy Space Center, FL 32899

ABSTRACT

Using the striking distance theory that lightning leaders will strike the nearest grounded point on their last jump to earth corresponding to the striking distance, the probability of striking a point on a structure in the presence of other points can be estimated. The lightning strokes are divided into deciles having an average peak current and striking distance. The striking distances are used as radii from the points to generate windows of approach through which the leader must pass to reach a designated point. The projections of the windows on a horizontal plane as they are rotated through all possible angles of approach define an area that can be multiplied by the decile stroke density to arrive at the probability of strokes with the window average striking distance. The sum of all decile probabilities gives the cumulative probability for all strokes.

The techniques can be applied to Kennedy Space Center (KSC) launch pad structures to estimate the lightning protection effectiveness for the crane, gaseous oxygen (GOX) vent arm, and other points. Streamers from sharp points on the structure provide protection for surfaces having large radii of curvature. The effects of nearby structures can also be estimated.

INTRODUCTION

The launch pads at KSC are protected by a 70-foot insulating fiber glass mast 5 feet in diameter located on the Fixed Service Structure with a lightning rod at the top of the mast. The rod is grounded 1,000 feet north and south of the tower by a 1/2-inch stainless steel cable called the catenary wire. The lightning protection system on Launch Pad 39A has been struck by lightning an average of three times per year since 1979. Probability calculations predicted about two strokes per year. The difference may be accounted for by the action of upward-going streamers that go out to meet the down-coming leader of the lightning stroke and meet it about 100 feet above the lightning rod. This effect increases the effective height of the mast and enhances its ability to attract strokes, especially the larger strokes. The probability of hitting the mast, without taking streamers into account, was calculated in a previous paper [1]. The probability of hitting selected points on the structure or the vehicle will now be considered using a similar technique to estimate the probability of hitting the selected point in the presence of other attracting points on the protection system, the structure, or the vehicle. This information can be used as a factor in a management decision, such as when to start fueling in relation to weather conditions.

Ignoring streamering effects and using the simple principle that lightning (in its last jump to earth at its striking distance) will hit the closest point on the mast, structure, vehicle, or ground, "windows" of approach through which the lightning must travel to reach the closest point are created by this assumption. The windows are largest in the most vulnerable direction of approach and then narrow and close as azimuth and stroke magnitude are changed. By calculating the projected area of these windows on the ground and multiplying by the stroke density for each stroke size increment (each direction increment) and summing all the increments, a cumulative probability for all strokes hitting a selected point can be determined. Launch Pad 39B at KSC is shown in figure 1.



Figure 1. Shuttle Vehicle on Launch Pad 39B With a Water Tower on the Right

CRANE WINDOWS OF APPROACH

To illustrate the probability calculation process, consider the calculation of the probability of hitting the tip of the crane boom, which is about 32.3 m (106 ft) from the lightning mast centerline and 30.5 m (100 ft) below the mast lightning rod tip, as shown in figure 2. Arcs of various striking distances from these two points intersect on the perpendicular bisector of the line joining the two points. The bisector is the upper boundary of "crane windows," which are sectors of approach where the lightning leaders are closer to the tip of the crane boom than to the mast lightning rod or the ground when the leader makes its last jump to earth. The lower boundary of the crane windows is a parabola with focus at the tip of the boom tip and the earth as directrix. This boundary is the locus of points equidistant from the boom and the earth. Below the parabola, all the strokes hit the earth and above it all hit the lightning mast. The crane windows close at the striking distance where the bisector intersects the parabola. For a mast height of 122 m (400 ft) and a boom height of 91.5 m (300 ft), this occurs at a striking distance of 390 m (1280 ft). The windows are also the locus of the center of a "rolling ball" (having the striking distance as radius) as it rolls over the tips of the boom and mast rod.

The technique used previously by Stahmann [1] for estimating the stroke probability divided all strokes into deciles (see table I) having average peak currents and striking distances. The attractive radius, R , was calculated from the striking distance S_d , and the height of the mast lightning rod, H , using the relationship:

$$R = \sqrt{2S_d H - H^2} \quad (1)$$

The attractive area was calculated and then multiplied by a relatively high stroke density of 20 strokes/km²/yr or 2×10^{-6} strokes/m²/yr/decile to obtain the stroke probability. The lightning rod is exposed to all strokes from all directions all year. However, to hit points below the rod (such as the crane tip), the lightning leader must enter through the associated window to hit the point. The windows change with direction of approach. The windows for the direction the crane boom is pointing is shown in figure 2. In other directions, up to 90 degrees from the crane pointing direction, the crane and mast rod tips are no longer coplanar and the distance difference to the leader is reduced, becoming zero at 90 degrees. Therefore, in other directions, the crane windows become smaller and close at lower striking distances. To calculate the probability of striking the crane (see table II), the areas of the horizontal projections of the crane windows for the various deciles were calculated as the projections were rotated ± 90 degrees from the pointing direction, assuming that the projection did not change. However, more detailed calculations indicated that this area is actually about one-half of that calculated because the windows and projections change as the direction of approach is rotated. The geometry of the window projected area calculations is discussed in the next section. The largest stroke deciles are listed first in tables II and III.

GOX VENT ARM AND SOLID ROCKET BOOSTER (SRB) WINDOWS OF APPROACH

Three possible strike points are shown in figure 3, the mast rod, the tip of a rod on the GOX vent arm, and the SRB nose below the vent arm. The geometry for calculating the probability of hitting the vent arm is shown in figure 4 where a fourth point is added, the tip of a lightning rod on the top of the nearby 87.2 m (286 ft) water tower 160 m (525 ft) from the lightning mast centerline in an easterly direction, 38 degrees from the north. Figure 3 shows the east-west plane. Lightning leaders must approach from the east to reach the vent arm or SRB tip.

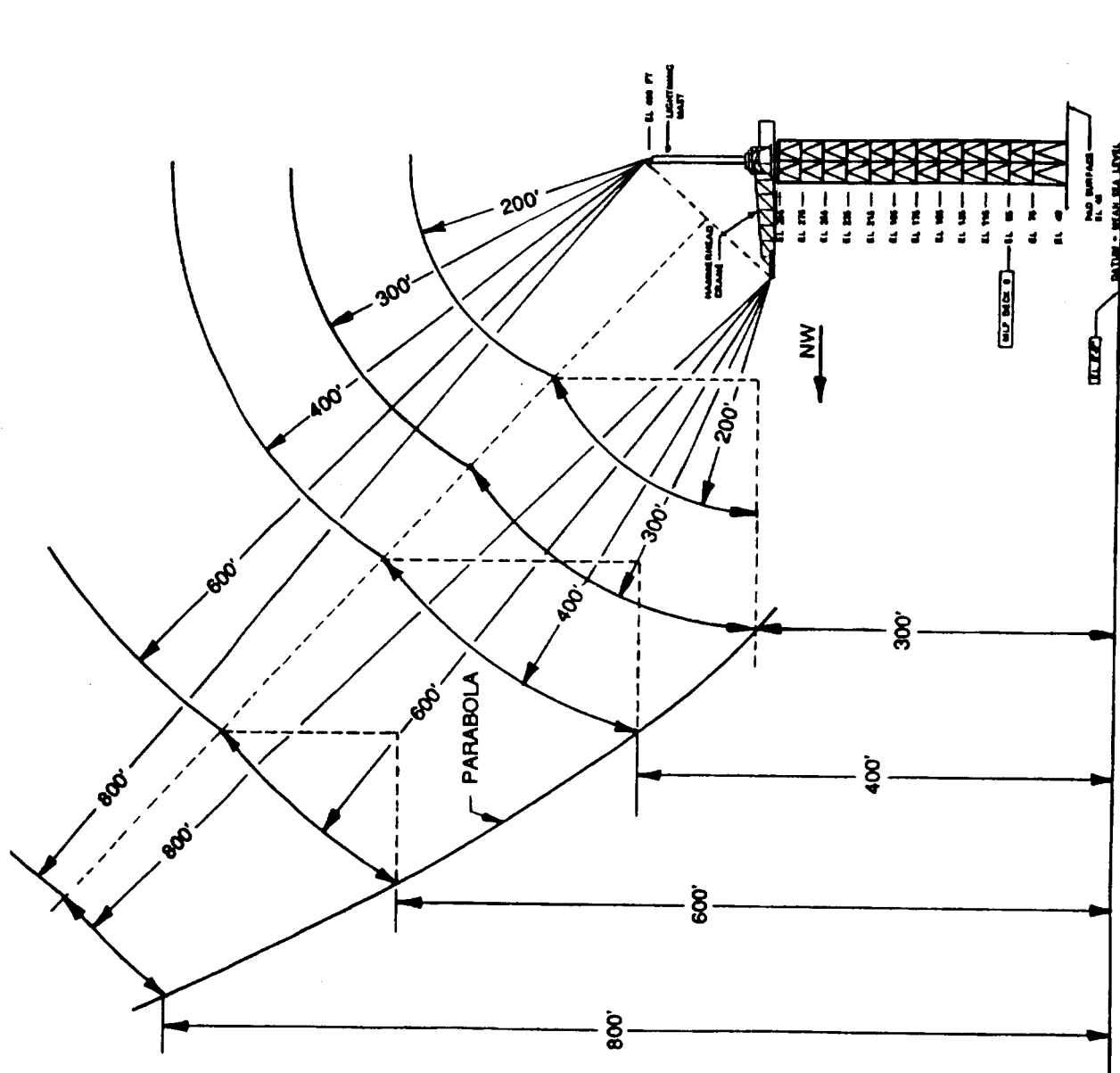


Figure 2. Crane Windows of Approach



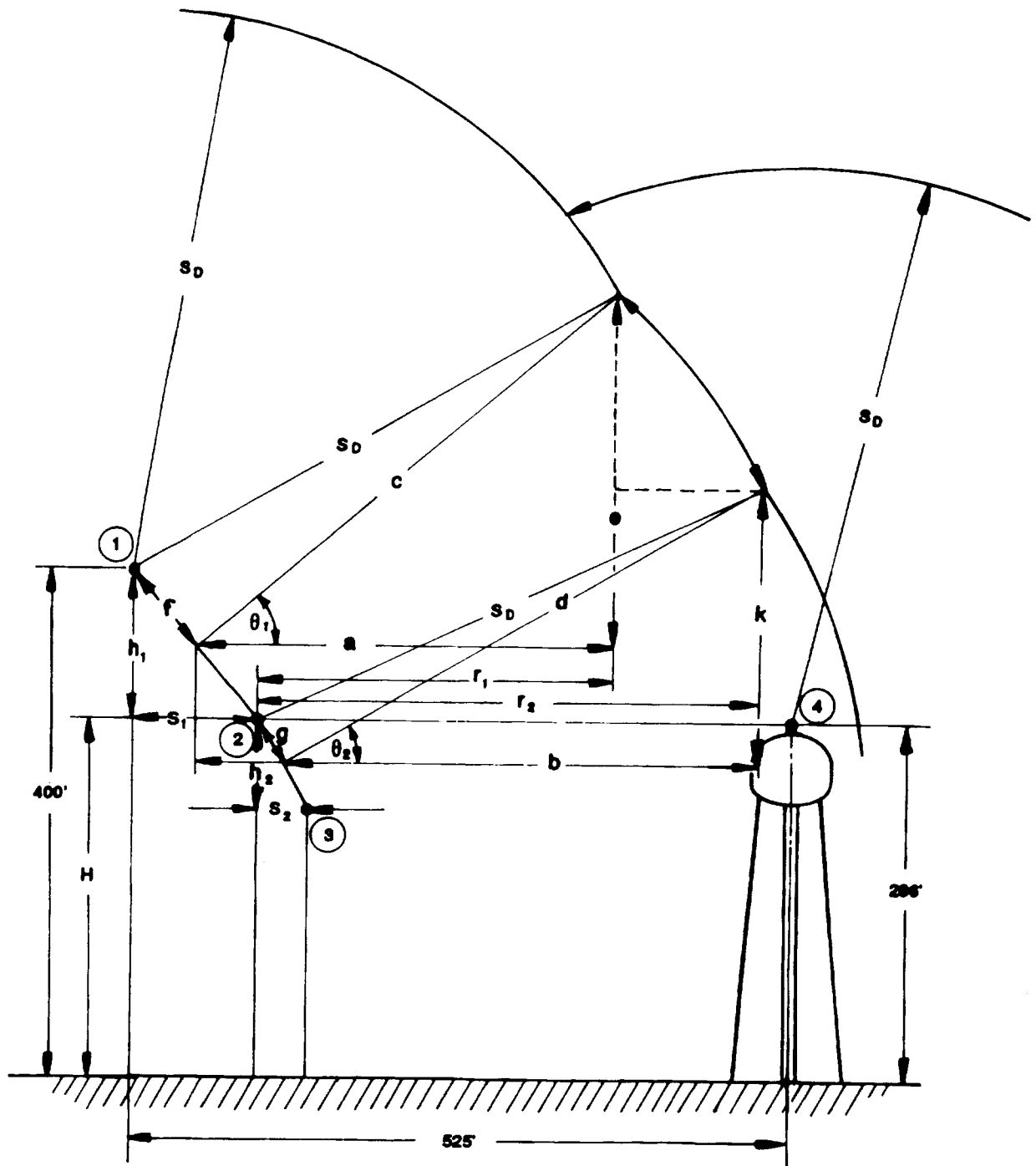


Figure 4. Geometry for Calculation of the ET Vent Window Projection on a Horizontal Plane

Table I. Probability of Striking a 122 m (400 ft) Tower

Decile	\bar{i}_{pk}	\bar{S}_d (m)	\bar{R} (m)	Area (m ²)	Decile Probability (Strokes/Year)	Cumulative Probability (Strokes/Year)	Years Per Strike
0-10	6.2 kA	46	46	6,648	0.01330	0.01330	75.2
10-20	12.9 kA	90	90	25,447	0.05089	0.06419	15.6
20-30	17.6 kA	115	115	41,548	0.08310	0.14729	6.8
30-40	22.7 kA	137	136	58,107	0.11621	0.2635	3.8
40-50	28.4 kA	161	156	76,454	0.15291	0.4164	2.4
50-60	35.2 kA	186	174	95,115	0.19023	0.6066	1.65
60-70	44.5 kA	217	195	119,459	0.23892	0.8455	1.18
70-80	57.0 kA	258	219	150,674	0.30135	1.1458	0.872
80-90	77.0 kA	318	250	196,350	0.39270	1.5395	0.65
90-100	112.0 kA	380	279	244,545	0.48909	2.0286	0.49

Table II. Probability of Striking the Crane

\bar{S}_d (ft)	c (ft)	a (ft)	r_1 (ft)	r_2 (ft)	Area (m ²)	Decile Probability (Strokes/Year)	Cumulative Probability (Strokes/Year)
1246	1244	853	800	811	2,587	0.005174	0.005174
1043	1040	714	661	732	14,518	0.029036	0.03421
846	843	578	525	646	20,726	0.041452	0.07566
712	708	486	433	581	21,899	0.043798	0.11946
610	606	415	362	525	21,129	0.042258	0.16172
528	523	359	306	476	19,474	0.038948	0.20067
449	443	304	251	424	17,015	0.034030	0.23470
377	370	254	201	369	14,010	0.028020	0.26272
295	286	196	143	295*	9,721	0.019442	0.28216
151	132	91	37.7	151*	3,122	0.006244	0.28840**

* When $S_d < H$, $r_2 = S_d$

** Once every 3.46 years

Table III. Probability of Striking the GOX Vent Arm Lightning Rod

\bar{S}_d (ft)	a (ft)	b (ft)	r_1 (ft)	r_2 (ft)	Area (m ²)	Decile Probability (Strokes/Year)	Cumulative Probability (Strokes/Year)
1043	772	**	717	711	Closed	--	--
846	625	**	571	629	10,181	0.020362	0.020362
712	525	**	471	566	14,424	0.028848	0.049210
610	449	**	394	513	15,716	0.031432	0.080642
528	387	**	333	466	15,540	0.031080	0.111722
449	328	**	273	416	14,362	0.028724	0.140446
377	243	**	219	364	12,374	0.024748	0.165194
295	210	344	156	295	8,691	0.017382	0.182576
151	95	204	40	150	3,036	0.006072	0.188648*

* Once every 5.3 years

** Ground stroke formula applies:

$$r_2 = \sqrt{2S_d H - H^2}$$

Windows are created for each of the three points. The SRB window starts to close at 74.7 m (245 ft) and closes at 164.9 m (541 ft) in this plane. The external tank (ET) vent windows close at about 313.7 m (1029 ft). The dimensions used are $H=85.4$ m (280 ft), $h_1=36.6$ m (120 ft), $h_2=10.7$ m (35 ft), $s_1=33.1$ m (108.5 ft), and $s_2=2.7$ m (9 ft). The formulas used for calculating the GOX vent arm window horizontal projected area are:

$$c = \sqrt{S_d^2 - f^2} \quad (2)$$

$$a = c \cos \theta_1 \quad (3)$$

$$d = \sqrt{S_d^2 - g^2} \quad (4)$$

$$b = d \cos \theta_2 + (s_1 + s_2) / 2 \quad (5)$$

$$r_1 = a - s_1 / 2 \quad (6)$$

$$r_2 = r_1 + b - a \quad (7)$$

where r_1 and r_2 are the attractive radii of the upper and lower window boundaries, respectively. The maximum attraction area for each decile produced by rotating the windows through all easterly directions ± 90 degrees from directly east is:

$$Area (m^2) < \pi / 2 (r_2^2 - r_1^2) / 3.28^2 \quad (8)$$

where r_1 and r_2 are in feet. As previously mentioned, this estimate of the area is a maximum since the windows close at shorter striking distances in other directions of approach other than directly east. The closure formulas are:

For the GOX vent arm, closure occurs at:

$$S_d = H + h_1 / 2 + e - \sqrt{c^2 + f^2} \quad \text{Solve for } e \text{ and } S_d \quad (9)$$

For the SRB, closure occurs at:

$$S_d = H - h_2 / 2 + k - \sqrt{d^2 + g^2} \quad \text{Solve for } k \text{ and } S_d \quad (10)$$

Of particular interest is the water tower shown in figure 4. This tower appears at first glance to offer little protection to the GOX vent arm. Actually, since the lightning leader must come in through the vent windows in order to reach the arm, it must pass within 85.4 m (280 ft) of the tower when approaching from a northeast direction (38 degrees). The water tower will then capture all strokes with striking distances greater than 85.4 m (280 ft) (80 percent of all strokes). From the south, the large rotating service structure (RSS) helps protect the ET so

that the probability of hitting the ET is reduced in this direction. Table III gives a maximum cumulative probability of hitting the GOX vent arm with lightning rod once every 5.3 years. Considering window closure and other factors, the maximum probability is closer to once in 10 years.

The above assumes continuous exposure for a full year. Since the vehicle is not present at all times and the GOX vent arm is retracted most of the time, the probability must be multiplied by the exposure percentage per year. For example, if the exposure time is 10 percent per year, the probability is reduced to once in 100 years or less if the exposure is less.

STREAMERING EFFECTS

An important factor in protecting the pad structures is the formation of streamers from the sharp points on the structures. The most prominent sharp point is the tip of the rod on the lightning mast. As shown in figure 5, the streamers go out to greet the down-coming leaders and meet in the characteristic "knee" shown. Figure 6 shows that, while the ET ogive is protected since it is within the NFPA 78 zone of protection based on a 30 m (100 ft) striking distance, the ET ogive is further protected by streamers from the GOX vent arm and the tip of the SRB. These streamers form earlier and move farther than any streamers that may form on the ogive.

CONCLUDING DISCUSSION

The probability of lightning striking points on a structure beneath the highest point can be estimated. Often the protected points can be approached only from a limited range of directions and along paths that have a large horizontal component. In a particular case, such as hitting a vehicle in the presence of a nearby structure, the structure may be modified to better protect the vehicle by improving the protective geometry and by encouraging the formation of protective streamers that can intercept the stroke leader using diverters in the high field regions.

REFERENCES

1. J. R. Stahmann, "Inside the Cone of Protection," International Aerospace and Ground Conference on Lightning and Static Electricity, Fort Worth, Texas, June 21 to 23, 1983, pp. 27-1 to 27-7.
2. R. H. Golde, "Lightning Conductor," Lightning, Volume 2, Chapter 17, Academic Press, 1977, pp. 545 to 576.

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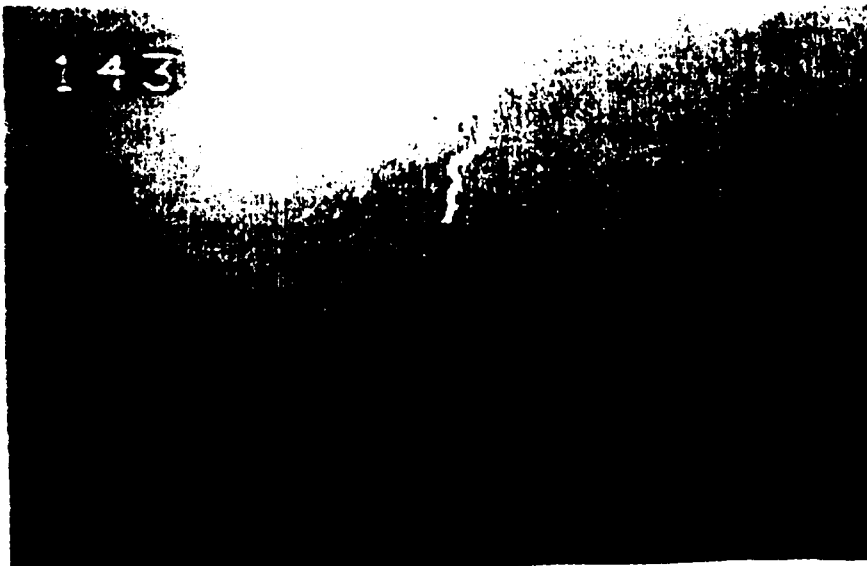


Figure 5. Two Strokes to the Pad Lightning Protection System Showing "Knee" Where an Upward-Going Streamer Meets a Down-Coming Leader

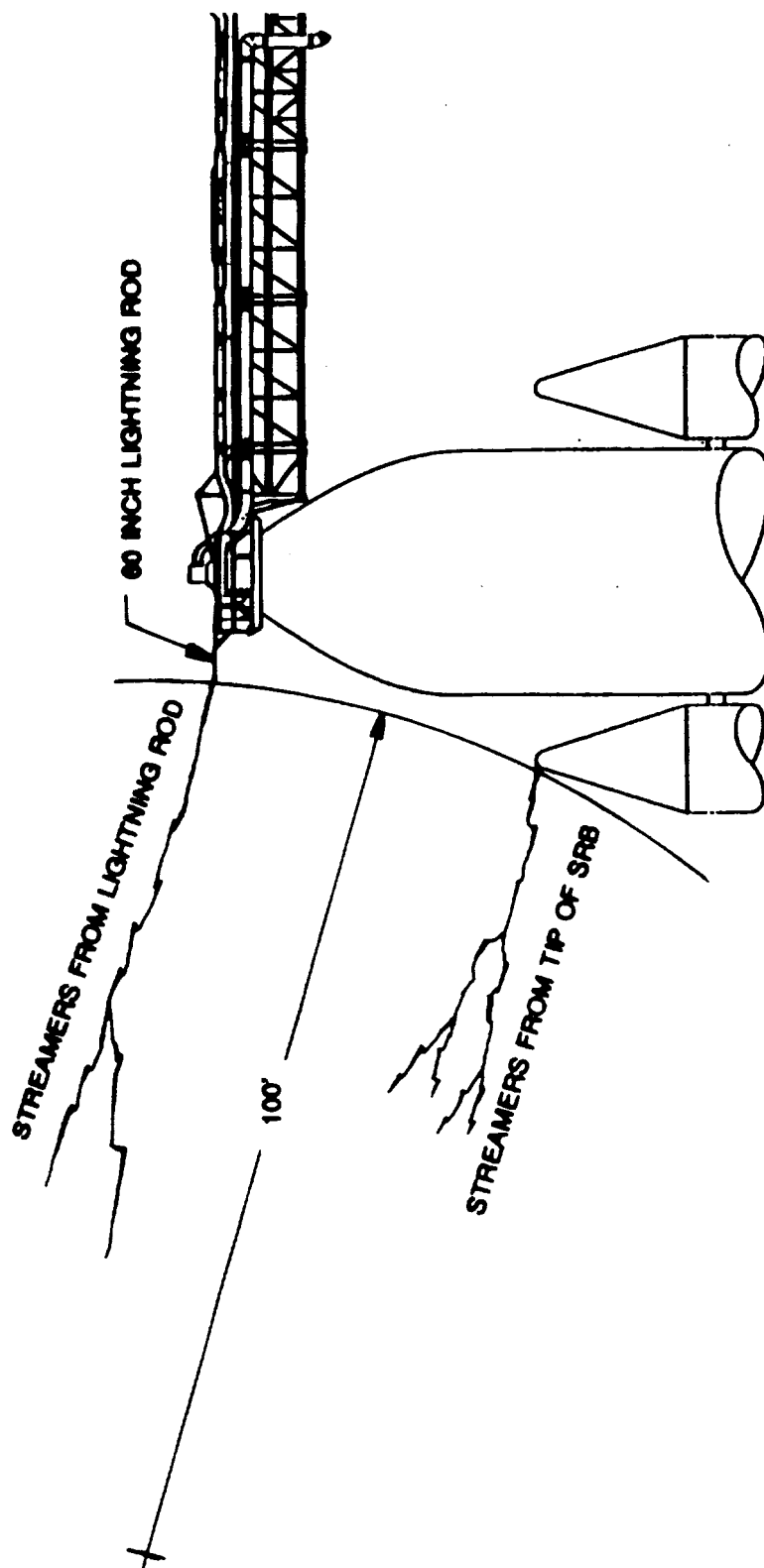


Figure 6. With the lightning rod on the GOX vent arm, the ET ogive is protected against strokes with $S_d \geq 100$ feet (streamers provide additional protection).